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Integration of Construction Quality in Makkah Municipality Pavement Management Maintenance System (PMMS)

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Abstract: Despite the fact that long-term pavement performance is highly dependent on the quality of construction, construction quality has rarely been addressed or considered in Pavement Management Systems (PMS). In this paper the impact of construction quality on pavement performance predictions, and hence the accuracy of PMS analysis, such as priority analysis and capital investment programs, is presented. This impact is demonstrated in this paper and found to be significant. A practical approach to integrate construction quality into PMS analysis is also presented in the paper.

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***Key words**: Capital programming and multi-year rehabilitation programs; Construction quality; Pavement Management Systems; Pavement performance indices; Performance prediction models*.

Introduction

The concept of Pavement Management Systems (PMS) has gained significant momentum in the last few decades. Numerous development and research studies have been performed to move PMS from a conceptual stage to a practical stage, which has allowed full implementation and increased utilization of many PMS features. For example, in addition to the inventory and performance monitoring components of PMS, multi-year priority analysis has become a routine PMS application for many highway agencies and state Departments of Transportation (DOTs). The advances made in PMS in the last few decades have allowed highway agencies to plan their future spending and select their capital improvement programs based on the analysis performed by their PMS to set priorities for improvements.

Performance prediction models are used in PMS to predict the future performance of different pavement sections. These models typically do not account for the construction quality and assume that the construction quality is the same for all pavement sections. Although most construction specifications allow diversions from standard conditions and apply either a penalty or a bonus in some cases, the impact of these diversions on the long term performance is not considered. Examples of these diversions include thickness tolerance and smoothness requirements.

One of the challenges facing PMS analysis and the accuracy of its outcomes, e.g. capital programs, is the gap between what is designed and what is actually constructed. Despite the fact that long-term pavement performance is based on what is actually constructed, accurate as-built data has rarely been considered in PMS. Pavement performance prediction, and hence the accuracy of the priority analysis and capital investment programs generated from PMS, would be greatly improved if accurate as-built data is considered. Utilizing the advancement made in Non-Destructive Testing (NDT) equipment, the impact of construction on pavement performance can be considered in PMS analysis.

Pavement construction quality has been previously assessed using a Construction Quality Index (CQI) and Construction Consistency Index (CCI) [1]. These two indices are functions of parameters such as constructed versus designed layer thickness, material parameters, consistency of layer thickness along the pavement section, etc. [1-3]. A scale of 0.0 to 1.0 is used for both CQI and CCI where 1.0 indicates the highest construction quality.

CQI or CCI have been used in PMS in order to assign an "as-built" condition and rate of deterioration for pavement sections. The "as-built" condition and rate of deterioration would impact the expected service life of pavement sections. Figs. 1 and 2 show an example of how this approach is implemented [1]. In these figures, actual field data of the structural performance of three projects with varying levels of construction quality were compared against a benchmark section with excellent construction quality. Fig. 1 shows the deterioration curves of the three construction quality classes, "Very Good", "Good" and "Fair", along with that of the "Benchmark" condition, in terms of Structural Adequacy Index (SAI). As can be seen from this figure, although the deterioration curves of all categories have the same initial value of SAI, however they have different rates of deteriorate with time. The expected service lives of these sections are impacted by the rate of deterioration with time, as can be seen from Fig. 2.

In this paper, another approach to integrate construction quality in PMS analysis is presented. In this approach, measurements of NDT equipment, such as Ground Penetrating Radar (GPR) and laser profilers, are used directly in PMS as indicators of construction quality. NDT measurements are integrated directly in PMS prediction models and used to define the "as-built" condition and rate of deterioration.

Components of Pavement Performance

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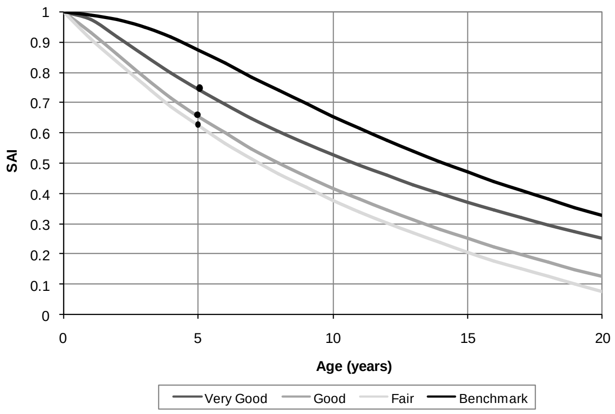

Fig. 1. Expected Performance of Sample Projects with Different Construction Quality [1].

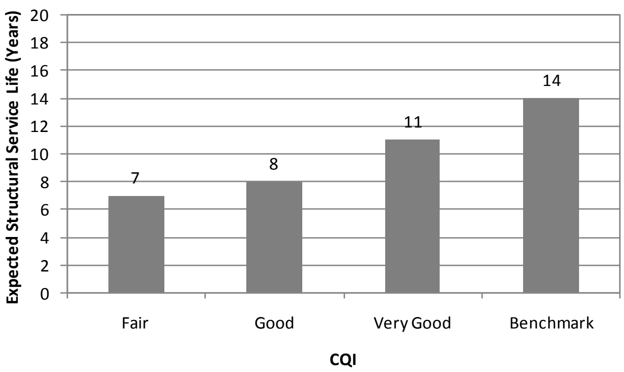

Fig. 2. Expected Service Life of Sample Projects with Different Construction Quality [1].

Pavement performance has two major components, functional and structural. Pavement functional performance deals with whether or not a pavement section provides users with a safe and smooth ride, while pavement structural performance deals with the number of load repetitions a pavement section can carry before it develops an unacceptable level of structural distresses. Functional performance is typically evaluated, and predicted in terms of the International Roughness Index (IRI) or other roughness indices, such as Ride Quality Index (RQI), that are strongly correlated with IRI, while structural performance is evaluated and predicted in terms of Structural Adequacy Index (SAI) [4]. A pavement section may be structurally adequate, yet have functional problems, and vice versa. Poor structural and/or functional performances are reflected on the pavement surface in the form of distresses, such as cracking.

Selection of appropriate rehabilitation treatments and the expected performance of the selected treatments are highly dependent on the functional and structural conditions of the pavement prior to implementing the treatment. For example, a pavement section is expected to have a much shorter service life if it were structurally deficient but receives a functional treatment. This is not the case when a structural improvement is implemented on a pavement section that needs only functional improvement, however the pavement life cycle cost in this case will be unnecessarily high (over design). With ever-increasing limitations on funding, every effort should be made to optimize the pavement life cycle cost. Therefore, both types of performance should be monitored and predicted to better control pavement life cycle costs and better select rehabilitation treatments.

In a study performed for the New Jersey DOT to assess the difference in PMS analysis for two scenarios, which are:

- PMS Scenario - Analysis is based only on functional performance measures (IRI and distresses)
- FWD Scenario - Analysis is based on both structural and functional performance measures (IRI, distresses and Falling Weight Deflectometer - FWD)

Approximately 330 centerline miles of the National Highway System (NHS) highways in New Jersey were considered in this study [5]. The functional performance measures used in the analysis included RQI (calculated from IRI) and distress data. The structural performance measures used in the analysis included the outcomes of the backcalculation analysis performed on FWD deflection measurements. Results of the comparison can be summarized as follows:

- The PMS and FWD results agreed for 27% (143 CL km) of the total length considered.
- The PMS rehabilitation results were found to be over-designed for 32% (169.6 CL km) of the total length considered, e.g. the PMS selected a strengthening rehabilitation activity while the FWD showed that the pavement had adequate structural capacity and no need for any structural improvement.
- The PMS rehabilitation results were found to be under-designed for 41% (217.4 CL km) of the total length considered, e.g. the PMS did not select a strengthening rehabilitation activity while the FWD showed that the pavement had inadequate structural capacity and a need for structural improvement.
- A similar comparison, indicating very similar trends, was also performed for the Virginia DOT [6]. These case studies highlight the importance of considering different performance measures in PMS.

Common Pavement Performance Measures in PMS

A comprehensive PMS would include some measures of both functional and structural pavement condition, along with the severity and extent of surface distresses. One unique use of surface distress data, in addition to converting the measurements into a single predictable index, is the determination of maintenance and pre-rehabilitation needs, such as crack sealing and patching. Typically, all these measures are then combined in an overall single performance index that is used in the economic analysis. The following is a brief description of common pavement performance measures.

Roughness Index (RI)

Ride quality, which is highly correlated with longitudinal roughness, is the most important performance parameter in the opinions of road users. Traditionally, roughness was evaluated in terms of a Pavement Serviceability Index (PSI). However, a few years ago the Federal Highway Administration (FHWA) adopted IRI as the national reporting index for roughness, i.e. all state DOTs are required to report the network condition to FHWA in terms of IRI. As a result, some state DOTs use only IRI to monitor and predict the functional performance of their pavements, while other DOTs use IRI, along with a DOT-specific normalized Roughness Index (RI) to get around the uniqueness of the IRI scale. As an example, IRI data can be re-scaled to fit a 0.0 to 1.0 scale, with 1.0 being a perfect section and 0.5 being a trigger for rehabilitation. This re-scaling would result in an RI that can be used to evaluate the current and future roughness condition.

Distress Index (DI)

Visual inspection is the most popular pavement evaluation method and is commonly used to monitor pavement performance. Visual inspection provides information about the type, severity, and extent of pavement distresses. This information is a good indicator of how a pavement section has performed to date. Also, it helps in selecting the appropriate maintenance activity. Issues related to visual inspection include the subjectivity of the measurements, repeatability, and the time and labor effort required to complete the survey. In addition, visual inspection is mainly concerned with visible symptoms and not necessarily with the cause or source of the problem.

Since pavement sections are expected to have different combinations of distresses (type, severity, and extent), detailed surface distress data, such as cracking and rutting, is converted to a single normalized index representing the overall distress condition of a section. This conversion allows sections with different distress types, severities, and extents to be compared. Many Distress Indices (DI) use a point-deduct system, i.e. a perfect pavement would have a score of 1.0 on a 0.0-1.0 scale, with points deducted from the perfect score based on the distress type, severity and extent. Prediction models are commonly used to predict the future DI.

Structural Adequacy Index (SAI)

Structural performance is the least used performance indicator in PMS. The main reasons for this are the cost and comparative complexity of obtaining the required data at the network level. A literature search performed a few years ago indicated that several models had been adopted by highway agencies to address the structural performance of pavements. These models included the Maximum Deflection Model, used by Minnesota DOT, Idaho DOT, and Alberta Infrastructure & Transportation [7]. In this model, deflection measurements are used to calculate a maximum allowable traffic level, which is then compared with the expected traffic. Another available SAI model **is** the South Carolina DOT SAI model [8]. In this model, FWD data is used to backcalculate the subgrade modulus and the pavement effective structural number (SNeff). This information is then used to determine the number of 18-kip axle load repetitions until failure using the American Association of State Highway and Transportation Officials (AASHTO) equation. Another SAI model that was developed for California DOT uses the effective gravel equivalent (GEeff) and the as-built gravel equivalent (GEas-built) [9]. These parameters are backcalculated from FWD data. A more recent SAI model that was developed for New Jersey DOT is function of SNeff, the as-built structural number (SNas-built), and the required structural number (SNreq) [4]. In this model, FWD data is used through backcalculation analysis to calculate SNeff, while the SNas-built is obtained from pavement thickness information used in the FWD backcalculation analysis. SNreq in this model is calculated using the AASHTO model, the subgrade modulus calculated from the FWD backcalculation analysis, and a traffic class that is a function of the road functional class. Prediction models are commonly used to predict the future SAI.

Overall Performance Index (OPI)

An overall pavement performance index is calculated as a function of the above mentioned indices (RI, DI, and SAI). An OPI provides a good picture of the current pavement condition and is typically used in the economic analysis of PMS. Since it is a single measure, it allows sections with different functional and structural conditions to be compared. OPI would be also used to compare, rank, and set priorities for different pavement sections within a network. In general, OPI is not predicted but rather calculated from the predicted individual performance indices (RI, DI, and SAI).

Integration of Construction Quality in PMS

Performance prediction models are used in PMS to predict the future performance of different segments. These models typically do not account for the construction quality and assume that the construction quality is the same for different segments. In reality, construction quality and as-built condition vary among pavement projects. This variation in construction quality and as-built condition has significant impact on the future performance of pavement sections [10, 11]. Therefore, considering the initial condition in predicting the future performance of pavements will have a positive impact on the accuracy of the predicted condition.

There are different approaches to consider construction quality and as-built condition. The implementation of a special index, such as a Construction Quality Index (CQI) or Construction Consistency Index (CCI) in PMS has been discussed earlier in the report [1]. Two approaches are presented in this reference [1], which are:

- Considering construction quality in PMS analysis through the use of a Construction Quality Index (CQI)
- The use of predetermined levels of construction quality based on functional class and segment length

It was concluded that the use of CQI will better address the construction quality issue, however it was recognized that a key challenge in such an approach is the development of a practical construction quality indicator. Due to the challenge with the first approach, the second approach was considered. Although the second approach is simpler, it was found that implementing this simpler approach could greatly improve the accuracy of PMS analysis that is performed to predict future pavement condition, and hence the future maintenance and rehabilitation needs, i.e. PMS needs analysis.

A different approach to integrate construction quality and as-built data in PMS is presented in this paper. In this approach, the measurements of some of the Non-Destructive Tests (NDT) are incorporated directly in the PMS performance prediction models. A limited set of NDT is considered a starting point, which includes:

- Ground Penetrating Radar (GPR) for layer thickness

- International Roughness Index (IRI) for rideability
- Distress survey for surface defects

Additional NDT can be easily incorporated in the same fashion.

Integrating NDT Measurements in PMS Performance Prediction Models

Fig. 3 shows some typical PMS performance prediction models. As can be seen from these models, a pavement section starts at 'as-built' condition, which is assumed in this figure to be 100% (perfect), and then deteriorates at different rates. These models are exponential and have the form presented in Eq. (1).

$$P = P_o - e^{\left(a - b \times c^t\right)} \quad (1)$$

where,
P = performance index,
P_o = P at age 0
t = fn(age)
a, b, c = model coefficients

The three model constants, a, b and c, are generated from the model fitting analysis based on measured field data. Fig. 4 shows an example of the model fitting analysis in which measured field data is presented along with the best fitted model. NDT measurements will be used to select the appropriate "as-built" condition and to adjust the rate of deterioration. A third dimension is added to the equation to account for the adjusted rate of deterioration as explained later in the paper.

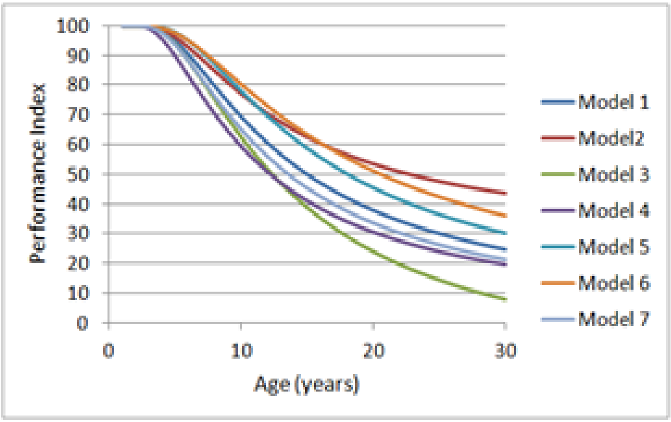

Fig. 3. Typical PMS Performance Prediction Models.

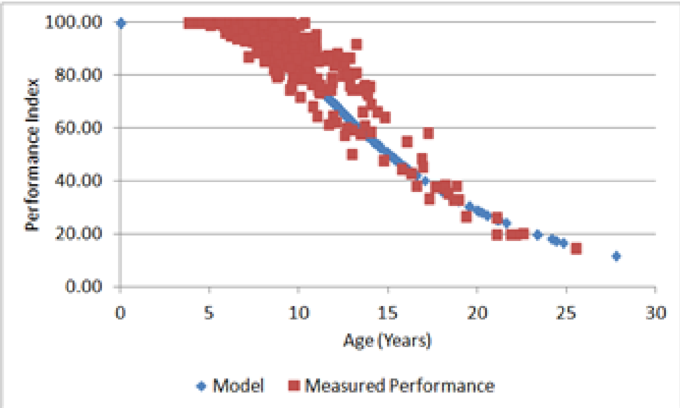

Fig. 4. Example of Model Fitting Analysis.

Integration of NDT Results with SAI Prediction Models

GPR data is integrated in the SAI prediction models by including an adjustment factor that represents the expected reduction in the pavement design life due to the variation in layer thickness. It is worth mentioning that the reduction in thickness will not impact the initial condition, i.e. $SAI_{initial}$ = 1.0, however it will have an impact on the long term performance.

The following are the steps followed to calculate the SAI adjustment factor:

- Calculate SN_{design} from the project workshop drawings
- Calculate $SN_{constructed}$ from the as-built GPR results
- SAI_{adjust} = f *($SN_{constructed}$ / SN_{design})^d, where d and f are regression factors
- d and f are calculated to reflect the difference in the expected service life based on the observed difference between the designed and constructed layer thickness.
- The revised prediction form model is presented in Eq. (2)

$$P = P_o - e^{\left(a - b \times (c^* SAIadjust)^t\right)} \quad (2)$$

Fig. 5 shows an example of integrating GPR results in SAI prediction models for a newly constructed flexible pavement section. The standard structural service life of a newly constructed pavement section is 20 years (noted by 1.00 in the legend of Fig. 5) if it were constructed as per the specifications. However, in case the constructed pavement section is thinner than the designed thickness, then a reduction in the actual structural service life is expected, i.e. actual service life is expected to be shorter than the designed service life (20 years).

In Fig. 5, the impact of constructing thinner layers than the designed layer thickness is presented for several cases, as measured using GPR (SAI_{adjust} of 0.99, 0.97, 0.96, 0.95 and 0.90). As can be seen from this figure, the expected structural service life for a pavement section that was constructed with a thickness less than the designed thickness, which resulted in SAI_{adjust} = 0.90 will be about 14 years instead of 20 years, while the corresponding number for SAI_{adjust} = 0.95 is about 16 years. This reduction in the expected structural service life is due to the reduction in the thickness of the constructed layers, i.e. the pavement structure is thinner than the structure needed to carry the expected traffic loads.

Similarly, a reduction in the structural service life of rehabilitation activities, such as overlays, is expected if the construction activity results in a layer thinner than the designed.

Fig. 6 shows the expected structural service life of a 50 mm (2 in) overlay. As can be seen from Fig. 6, the standard structural service life of the overlay is about 10 years. This service life is expected to be reduced if the constructed overlay thickness is less than 50 mm (2 in), as shown in the figure.

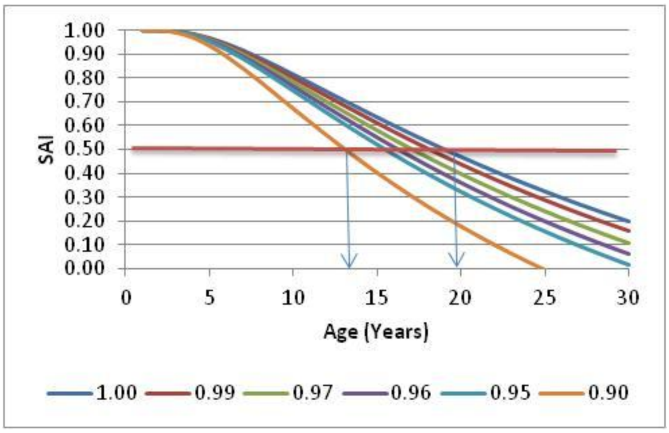

Fig. 5. Impact of Thickness Reduction on Expected Structural Service Life of New Pavements.

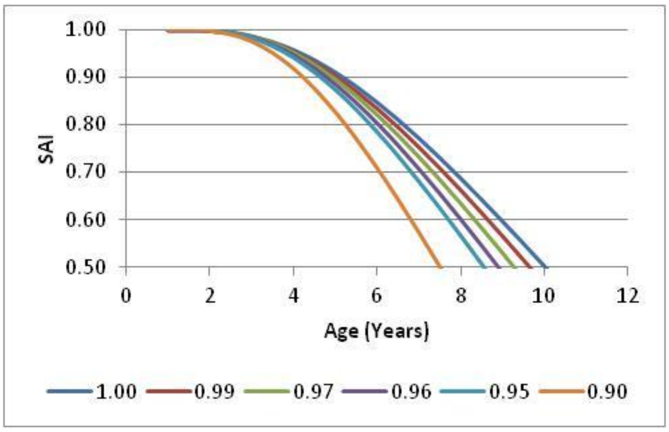

Fig. 6. Impact of Thickness Reduction on Expected Structural Service Life of Overlays.

Integrating of NDT Results with RI Prediction Models

Results of smoothness acceptance tests, in terms of IRI, are integrated in the RI prediction models in two ways, as follows:

- As-built RI ($RI_{initial}$.) will be set equal to the value corresponding to the measured IRI during smoothness acceptance tests.
- Higher rate of deterioration is expected and applied using an approach similar to that used in SAI prediction model

Fig. 7 shows some examples of newly constructed pavement sections with a range of $RI_{initial}$. In this figure, $RI_{initial}$ ranged from 1.0 (meeting the smoothness specifications requirements) to $RI_{initial}$ = 0.75 (equivalent to IRI in the range of 2.0 m/km). As can be seen, a section that is built rough and does not meet the smoothness specifications, such as that with $RI_{initial}$ = 0.75, is expected to have functional service life of only 9 years, instead of 20 years. A few examples of varying smoothness are presented in Fig. 8 for overlaid pavements. As can be seen, the functional service life of an overlaid pavement section can be reduced from 10 years (standard service life for this type of overlays) to 6 years because of the initial roughness of the overlaid pavement. A pavement section with very high initial roughness, such as this level, is typically rejected. However, in some construction specifications the agency may

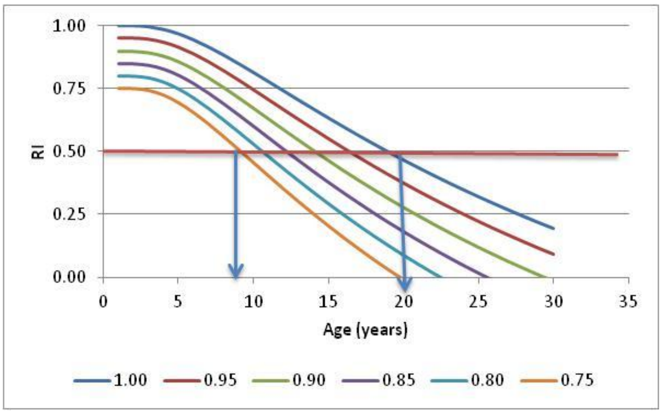

Fig. 7. Impact of Lack of Smoothness on Expected Functional Service Life of New Pavements.

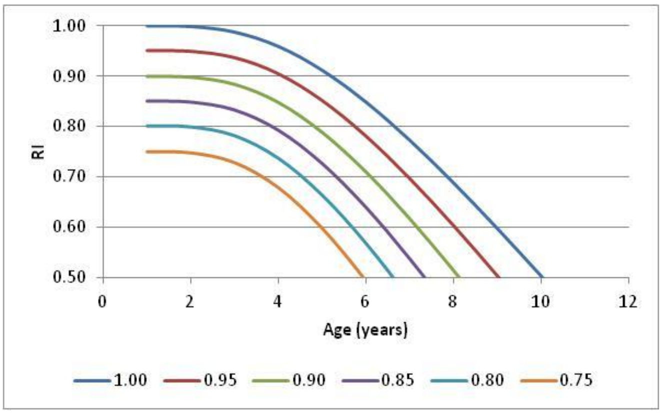

Fig. 8. Impact of Lack of Smoothness on Expected Functional Service Life of Overlays.

accept a section like that after applying a very high penalty on the contractor. In such a case, PMS analysis has to account for the poor initial condition of this section and model it accordingly.

Integrating of NDT Results with DI Prediction Models

Similar to RI, $DI_{initial}$ is integrated in the DI prediction models in the following two ways:

- As-built DI will be set equal to the value of $DI_{initial}$
- Higher rate of deterioration using an approach similar to that used in SAI prediction model

Integrating of NDT Results with Overall Performance Index (OPI)

As mentioned earlier, an overall pavement performance index is always used in PMS to provide a good picture of the overall pavement condition and is used in the economic analysis of PMS. OPI is also used to compare pavement sections with different structural, functional and distress conditions, to set their priorities and to rank them. OPI is calculated as a function of the three indices (RI, DI, and SAI). Many functions are commonly used to calculate OPI from SAI, RI and DI. These functions include:

- $OPI = a*SAI + b*RI + c*DI$

where, a, b and c are the weights of SAI, RI and DI, respectively and their sum is equal to one.

- OPI = Average (SAI, RI and DI)
- OPI = Minimum (SAI, RI and DI)

Figs. 9 and 10 show the impact of construction quality on OPI calculated as the average (SAI, RI and DI) and minimum (SAI, RI and DI), respectively. In these figures four cases are presented, which are:

- A pavement section meets the construction specifications of thickness, IRI and distresses, i.e. no construction issues.
- A pavement section does not meet the construction specifications as follows:

a. $SAI_{adjust} = 0.95$, $RI_{initial} = 0.95$ and $DI_{initial} = 0.95$
b. $SAI_{adjust} = 0.95$, $RI_{initial} = 0.85$ and $DI_{initial} = 0.95$
c. $SAI_{adjust} = 0.9$, $RI_{initial} = 0.8$ and $DI_{initial} = 0.85$

As can be seen from these figures, the expected service life of the pavement section that meets all the construction specifications is about 20 years. However, the expected pavement service lives for the above listed cases (a, b and c) based on the two OPI models (average and minimum) are:

- Expected overall service lives for Cases "a", "b" and "c" based on OPI equal to the average of SAI, RI and DI are 16, 14.5 and 12 years, respectively.
- Expected overall service lives for Cases "a", "b" and "c" based on OPI equal to the minimum of SAI, RI and DI are 15.5, 12.5 and 10.5 years, respectively.

The above presented cases highlight the significance of the impact of the construction quality on the expected pavement service life.

Impact of Construction Quality on PMS Network Level Analysis

The following example is provided to demonstrate the impact of construction quality on PMS network level analysis. In this example, data was randomly generated to create a hypothetical small highway network of 52 sections and about 280 lane miles. SAI, RI, and DI values were calculated for this data set and an OPI was determined as being the average of the three performance indices (SAI, RI and DI). These indices were used in the subsequent analysis to evaluate performance and identify the rehabilitation needs. Two scenarios are considered in this example, as follows:

- Standard Scenario (SS), where construction quality is not considered.
- Construction Quality Scenario (CQS), where construction quality is considered through the as-built SAI, RI, DI and OPI ($SAI_{initial}$, $RI_{initial}$, $DI_{initial}$ and $OPI_{initial}$), as explained earlier in the paper.

Table 1 shows a list of the sections and their basic attributes. In the same table, the results of the needs analysis based on the Standard Scenario (SS) are presented. These results include the need year at which a section will be triggered, i.e. candidate for rehabilitation, and the estimated rehabilitation cost. It is worth mentioning that the results presented in Table 1 are the typical PMS results and do not account for the construction quality of the sections.

Fig. 11 summarizes the needs analysis results. In this figure, the yearly budgets required for the triggered sections are presented.

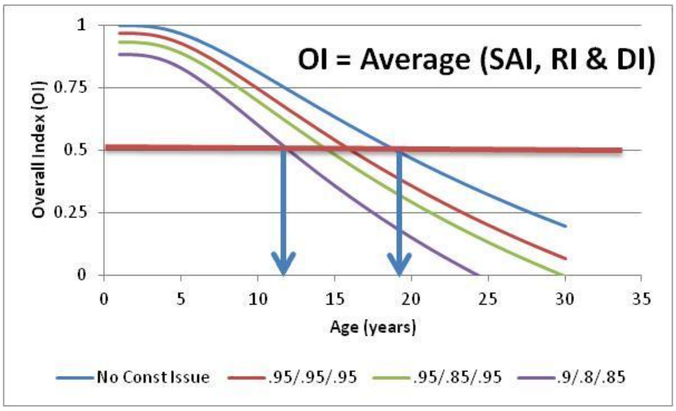

Fig. 9. Impact of Construction Quality on Overall Performance Index (Average of all Performance Indices).

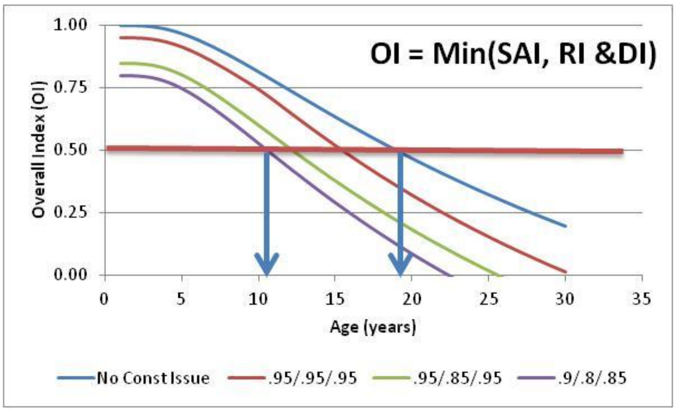

Fig. 10. Impact of Construction Quality on Overall Performance Index (Minimum of all Performance Indices).

An annual budget of $8 million is assumed for this network. Priority analysis was performed using $8 million annual budget. The multi-year rehabilitation program resulted from the priority analysis is presented in Table 2. Fig. 12 shows the annual budgets associated with the multi-year rehabilitation program presented in Table 2.

Based on the above presented analysis, the network will be at almost "zero backlog" if the rehabilitation program presented in Table 2 is implemented. However, the picture might be different if the as-built condition is considered in the prediction of the future performance and needs analysis.

Table 3 shows the same network sections along with their as-built performance indices ($SAI_{initial}$, $RI_{initial}$, and $DI_{initial}$). The Needs analysis was repeated considering the as-built condition using the approach presented earlier in this paper. Results of the needs analysis considering the as-built condition are presented in Table 3. As can be seen from Table 3, many of the sections will be triggered earlier if the as-built condition is considered. Fig. 13 shows the required annual budget when the as-built condition is considered. Priority analysis was repeated using $8 million annual budget. The resulted multi-year rehabilitation program is presented in Table 4. In this table, sections that are in backlog situation are colored in Red.

A section is considered in backlog situation if the budget year (when the funds will be available to perform the required rehabilitation) is beyond the trigger or need year (when the section condition reaches a stage that requires performing rehabilitation).

Table 1. Standard Scenario (SS) Needs Analysis.

Highway Segment ID	Length (mile)	Age (Years)	Number of Lanes	Last Activity (Construction or Overlay)	Need Year	Cost ($)
43234	1.10	9	2	O	2013	605,000
55734	5.64	9	3	O	2013	5,072,727
14323	0.21	9	2	O	2013	93,396
12436	0.58	9	2	O	2013	262,436
14346	1.06	8	2	O	2014	476,321
83848	2.40	7	3	O	2015	2,160,000
12390	0.64	7	2	O	2015	289,528
48384	6.20	6	2	O	2016	3,410,000
33991	4.40	6	2	O	2016	2,420,000
54564	6.70	6	3	O	2016	6,030,000
43702	6.82	6	2	O	2016	3,751,000
24134	3.18	6	2	O	2016	1,750,000
55968	6.09	6	2	O	2016	3,654,545
13245	0.58	6	2	O	2016	350,943
15503	0.71	6	2	O	2016	317,547
14393	1.39	6	2	O	2016	625,755
15550	0.87	6	2	O	2016	393,654
14417	0.41	6	2	O	2016	185,249
12460	0.75	6	2	O	2016	339,623
50002	5.10	5	2	O	2017	3,060,000
23900	3.41	5	2	O	2017	1,875,500
12343	0.40	14	2	C	2017	178,302
14370	1.29	5	2	O	2017	579,057
23666	2.64	4	2	O	2018	1,452,000
13399	0.83	4	2	O	2018	498,113
15596	1.15	4	3	O	2018	775,729
23432	2.10	12	2	C	2019	1,155,000
43936	7.37	3	2	O	2019	4,053,500
44404	2.82	12	2	C	2019	1,690,909
24602	4.00	3	2	O	2019	2,400,000
15479	0.73	3	2	O	2019	326,887
12366	0.50	3	2	O	2019	224,151
15526	0.91	3	2	O	2019	410,943
15573	1.06	12	2	C	2019	478,559
14440	0.53	3	2	O	2019	239,280
32450	3.10	11	2	C	2020	1,705,000
55032	3.74	2	2	O	2020	2,244,000
55500	4.64	11	2	C	2020	2,781,818
19000	0.66	2	2	O	2020	396,226
15000	0.96	11	2	C	2020	577,358
12413	0.60	11	2	C	2020	270,154
15456	1.26	10	2	C	2021	758,491
14838	1.17	8	2	C	2023	701,887
55266	4.84	7	3	C	2024	4,356,000
13492	0.64	7	2	C	2024	384,906
90002	3.50	6	3	C	2025	3,150,000
43468	5.61	6	2	C	2025	3,085,500
44170	2.18	6	2	C	2025	1,200,000
24368	3.09	6	2	C	2025	1,854,545
18384	0.45	6	2	C	2025	271,698
34927	3.40	3	2	C	2028	1,700,000
54798	3.85	3	2	C	2028	2,310,000

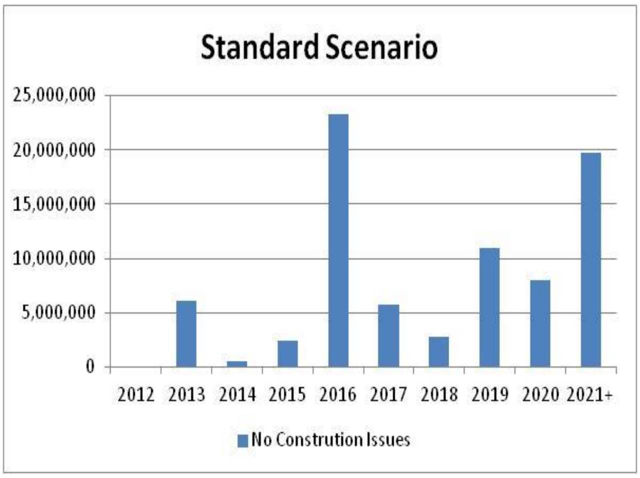

Fig. 11. Needs Analysis Based on Standard Scenario.

Table 2. Rehabilitation Program Based on Priority Analysis (As-Built Condition Not Considered).

Highway Segment ID	Length (mile)	Age (Years)	Number of Lanes	Last Activity (Construction or Overlay)	Need Year	Budget Year	Cost ($)
43234	1.10	9	2	O	2013	2013	605,000
55734	5.64	9	3	O	2013	2013	5,072,727
14323	0.21	9	2	O	2013	2013	93,396
12436	0.58	9	2	O	2013	2013	262,436
14346	1.06	8	2	O	2014	2014	476,321
83848	2.40	7	3	O	2015	2014	2,160,000
12390	0.64	7	2	O	2015	2014	289,528
48384	6.20	6	2	O	2016	2014	3,410,000
33991	4.40	6	2	O	2016	2014	2,420,000
13245	0.58	6	2	O	2016	2014	350,943
15503	0.71	6	2	O	2016	2014	317,547
15550	0.87	6	2	O	2016	2014	393,654
14417	0.41	6	2	O	2016	2015	185,249
54564	6.70	6	3	O	2016	2015	6,030,000
24134	3.18	6	2	O	2016	2015	1,750,000
43702	6.82	6	2	O	2016	2016	3,751,000
55968	6.09	6	2	O	2016	2016	3,654,545
14393	1.39	6	2	O	2016	2016	625,755
12460	0.75	6	2	O	2016	2017	339,623
50002	5.10	5	2	O	2017	2017	3,060,000
23900	3.41	5	2	O	2017	2017	1,875,500
12343	0.40	14	2	C	2017	2017	178,302
14370	1.29	5	2	O	2017	2017	579,057
23666	2.64	4	2	O	2018	2017	1,452,000
13399	0.83	4	2	O	2018	2017	498,113
15596	1.15	4	3	O	2018	2018	775,729
23432	2.10	12	2	C	2019	2018	1,155,000
43936	7.37	3	2	O	2019	2018	4,053,500
44404	2.82	12	2	C	2019	2018	1,690,909
15479	0.73	3	2	O	2019	2018	326,887
24602	4.00	3	2	O	2019	2019	2,400,000
12366	0.50	3	2	O	2019	2019	224,151
15526	0.91	3	2	O	2019	2019	410,943
15573	1.06	12	2	C	2019	2019	478,559
14440	0.53	3	2	O	2019	2019	239,280
32450	3.10	11	2	C	2020	2019	1,705,000
55032	3.74	2	2	O	2020	2019	2,244,000
19000	0.66	2	2	O	2020	2019	396,226
55500	4.64	11	2	C	2020	2020	2,781,818
15000	0.96	11	2	C	2020	2020	577,358
12413	0.60	11	2	C	2020	2020	270,154
15456	1.26	10	2	C	2021	2020	758,491
14838	1.17	8	2	C	2023	2020	701,887

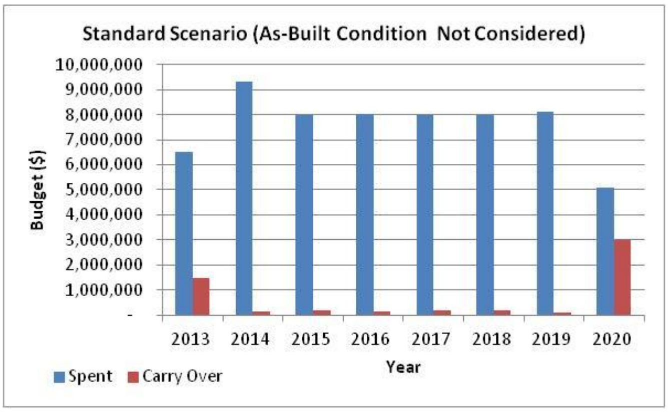

Fig. 12. Priority Analysis Results.

As can be seen from Table 4, most of the sections will be designated as backlog.

This example demonstrates a challenge that faces many highway agencies. Although the agency performs PMS priority analysis to plan its future spending to achieve a desired goal, e.g. "zero-backlog", however the agency fails in achieving such goal.

The main reason for not achieving the desired goal is related to the low accuracy of the PMS predication models. This low accuracy is resulted from ignoring the as-built condition of the pavement

Table 3. Needs Analysis Based on As-Built Condition.

Highway Segment ID	Length (mile)	Age (Years)	Need Year without Considering As-Built Condition	$SAI_{initial}$	$RI_{initial}$	$DI_{initial}$	RL	Need Year Considering As-Built Condition
12436	0.58	9	2013	1.00	0.85	0.95	-	2012
14323	0.21	9	2013	0.85	0.90	1.00	-	2012
43234	1.10	9	2013	0.90	0.90	0.90	-	2012
55734	5.64	9	2013	0.90	0.90	0.85	-	2012
14346	1.06	8	2014	0.90	0.95	0.90	1	2013
12390	0.64	7	2015	1.00	0.90	1.00	3	2015
83848	2.40	7	2015	0.95	1.00	0.95	2	2014
12460	0.75	6	2016	0.85	0.90	1.00	2	2014
13245	0.58	6	2016	1.00	0.90	0.95	4	2016
14393	1.39	6	2016	0.90	0.95	1.00	3	2015
14417	0.41	6	2016	0.95	1.00	0.95	3	2015
15503	0.71	6	2016	0.95	1.00	1.00	3	2015
15550	0.87	6	2016	0.95	1.00	0.95	3	2015
24134	3.18	6	2016	1.00	1.00	1.00	4	2016
33991	4.40	6	2016	0.85	0.85	0.85	1	2013
43702	6.82	6	2016	1.00	0.95	1.00	4	2016
48384	6.20	6	2016	1.00	0.85	1.00	4	2016
54564	6.70	6	2016	0.90	0.90	0.90	2	2014
55968	6.09	6	2016	0.85	0.85	0.90	2	2014
12343	0.40	14	2017	0.90	0.90	0.85	-	2012
14370	1.29	5	2017	1.00	1.00	1.00	5	2017
23900	3.41	5	2017	0.95	0.95	1.00	4	2016
50002	5.10	5	2017	0.90	0.85	0.95	3	2015
13399	0.83	4	2018	1.00	0.90	1.00	6	2018
15596	1.15	4	2018	0.85	0.95	1.00	4	2016
23666	2.64	4	2018	1.00	0.90	1.00	6	2018
12366	0.50	3	2019	0.95	0.95	0.90	6	2018
14440	0.53	3	2019	0.85	0.90	1.00	5	2017
15479	0.73	3	2019	0.90	0.95	0.90	6	2018
15526	0.91	3	2019	1.00	0.95	1.00	7	2019
15573	1.06	12	2019	1.00	0.90	0.95	5	2017
23432	2.10	12	2019	0.90	0.90	0.90	2	2014
24602	4.00	3	2019	0.90	0.95	0.90	6	2018
43936	7.37	3	2019	1.00	1.00	0.85	7	2019
44404	2.82	12	2019	0.90	0.95	0.90	3	2015
12413	0.60	11	2020	0.90	1.00	1.00	6	2018
15000	0.96	11	2020	0.90	0.85	0.90	3	2015
19000	0.66	2	2020	0.90	0.85	0.85	6	2018
32450	3.10	11	2020	1.00	0.85	1.00	6	2018
55032	3.74	2	2020	1.00	0.90	1.00	8	2020
55500	4.64	11	2020	0.85	0.85	1.00	3	2015
15456	1.26	10	2021	1.00	0.90	1.00	8	2020
14838	1.17	8	2023	0.95	0.90	0.95	8	2020
13492	0.64	7	2024	0.95	0.90	0.90	8	2020
55266	4.84	7	2024	0.85	1.00	0.95	8	2020
18384	0.45	6	2025	0.90	0.95	0.90	9	2021
24368	3.09	6	2025	0.85	0.90	0.85	7	2019
43468	5.61	6	2025	0.95	0.90	1.00	11	2023
44170	2.18	6	2025	0.85	0.90	0.85	7	2019
90002	3.50	6	2025	1.00	0.95	0.90	11	2023
34927	3.40	3	2028	0.95	1.00	1.00	15	2027
54798	3.85	3	2028	0.95	0.85	0.95	12	2024

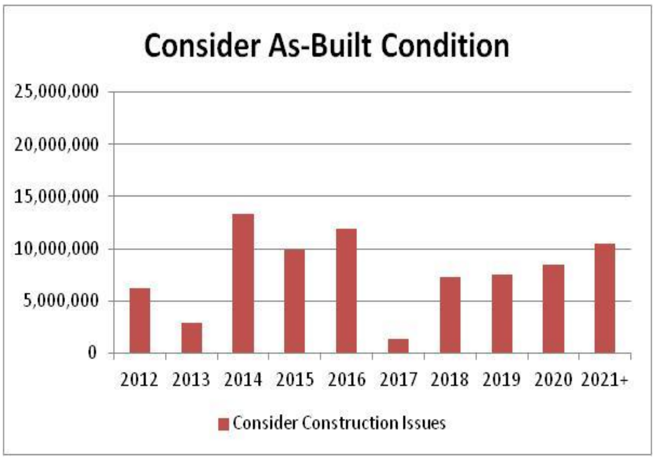

Fig. 13. Budget Requirements Based on As-Built Condition.

sections and the impact of this as-built condition on the long term performance. It is worth mentioning that since we do not build pavements in plants or factories, variations along pavements is very expected. Ignoring this variation and its impact on long term performance is not justifiable.

Summary, Conclusions and Recommendations

Ignoring the as-built condition creates a gap between predicted and actual needs. A section that has been built to a standard condition is expected to have a service life close to its design life. However, a section that has been built to less than the standard condition is expected to have shorter service life. In other words, the initial or as built condition has a significant impact on the section service life and when it will be triggered for rehabilitation.

In this paper a simplistic approach to consider the as-built condition in PMS analysis is presented. As-built condition is assessed using NDT measurements that include Ground Penetrating Radar (GPR), profilers and distress surveys. An approach is presented in the paper to integrate NDT measurements directly in the PMS performance prediction models.

A hypothetical small highway network of 52 sections and about 280 lane miles is used to demonstrate the impact of ignoring the as-built condition on the accuracy of the PMS prediction and multi-year rehabilitation programs. The example clearly highlighted the significance of considering the as-built condition on the accuracy of the PMS outcomes.

Table 4. Rehabilitation Program Based on Priority Analysis (As-Built Condition Considered).

Highway Segment ID	Length (mile)	Age (Years)	Number of Lanes	Last Activity (Construction or Overlay)	Need Year Consider As-Built	Budget Year	Cost ($)
43234	1.10	9	2	O	2012	2013	605,000
55734	5.64	9	3	O	2012	2013	5,072,727
14323	0.21	9	2	O	2012	2013	93,396
12343	0.40	14	2	C	2012	2013	178,302
12436	0.58	9	2	O	2012	2013	262,436
14346	1.06	8	2	O	2013	2013	476,321
33991	4.40	6	2	O	2013	2014	2,420,000
83848	2.40	7	3	O	2014	2014	2,160,000
55968	6.09	6	2	O	2014	2014	3,654,545
12460	0.75	6	2	O	2014	2014	339,623
54564	6.70	6	3	O	2014	2015	6,030,000
23432	2.10	12	2	C	2014	2015	1,155,000
15000	0.96	11	2	C	2015	2015	577,358
15503	0.71	6	2	O	2015	2015	317,547
14393	1.39	6	2	O	2015	2015	625,755
50002	5.10	5	2	O	2015	2016	3,060,000
55500	4.64	11	2	C	2015	2016	2,781,818
44404	2.82	12	2	C	2015	2016	1,690,909
14417	0.41	6	2	O	2015	2016	185,249
12390	0.64	7	2	O	2015	2016	289,528
15550	0.87	6	2	O	2015	2017	393,654
48384	6.20	6	2	O	2016	2017	3,410,000
43702	6.82	6	2	O	2016	2017	3,751,000
13245	0.58	6	2	O	2016	2017	350,943
23900	3.41	5	2	O	2016	2018	1,875,500
24134	3.18	6	2	O	2016	2018	1,750,000
14370	1.29	5	2	O	2017	2018	579,057
15573	1.06	12	2	C	2017	2018	478,559
14440	0.53	3	2	O	2017	2018	239,280
32450	3.10	11	2	C	2018	2018	1,705,000
23666	2.64	4	2	O	2018	2018	1,452,000
15596	1.15	4	3	O	2016	2019	775,729
24602	4.00	3	2	O	2018	2019	2,400,000
19000	0.66	2	2	O	2018	2019	396,226
13399	0.83	4	2	O	2018	2019	498,113
15479	0.73	3	2	O	2018	2019	326,887
12366	0.50	3	2	O	2018	2019	224,151
12413	0.60	11	2	C	2018	2019	270,154
44170	2.18	6	2	C	2019	2019	1,200,000
24368	3.09	6	2	C	2019	2019	1,854,545
43936	7.37	3	2	O	2019	2020	4,053,500
15526	0.91	3	2	O	2019	2020	410,943
55032	3.74	2	2	O	2020	2020	2,244,000
14838	1.17	8	2	C	2020	2020	701,887
13492	0.64	7	2	C	2020	2020	384,906
55266	4.84	7	3	C	2020	2021	4,356,000
15456	1.26	10	2	C	2020	2021	758,491

As outlined in the example, the planned budget and multi-year rehabilitation program are supposed to keep the network with almost "zero" backlog. However it is expected that this goal will not be achieved. Sections will be in need for maintenance and rehabilitation earlier than the planned program because of their initial or as-built condition. This will create undesired situations to the highway agency and make it not capable of managing the network condition as desired and planned. It is strongly recommended to consider the as-built condition in PMS, specifically in needs analysis and multi-year rehabilitation programs.

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